NOISE REDUCTION TECHNIQUES IN PULSE WIDTH MODULATED INDUCTIVE SWITCHING SYSTEMS OF PSLV

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ABSTRACT

The subject of this paper is the Techniques employed in Polar Satellite Launch Vehicle to reduce electromagnetic interference in Control Systems which have pulse width modulated inductive switching systems. There are 3 such control systems in PSLV. PWM Servo amplifiers are generally preferred in Control systems for better efficiency and to reduce dissipation losses. However, PWM signal itself creates an EMI environment. Hence care must be taken in the design phase of control electronics to minimise the EMI effects of PWM. This includes radiation effects as well as interference due to switching spikes. In general, the main sources of interferences are the PWM switching signal, inductive switching of motors by PWM with heavy currents, and subsequent generation of large magnetic fields, ground loop formations between power and signal grounds and improper bunching and harnessing of cables. The paper attempts to categorise the various inteference sources, and to share the experiences in PSLV programme as to how in the design phase these interferences are taken care of. The forms of inteferences are studied and the methods of noise reduction techniques are illustrated in a case study of 3rd stage control system.

A. INTRODUCTION

Polar Satellite Launch Vehicle (PSLV) comprises four stages, and all the four stages are provided with control systems for controlling the vehicle in all the 3 axes viz., Pitch, Yaw & Roll. The first, Third and Fourth stages of PSLV employ Pulse Width Modulated (PWM) Power amplifiers in the driving circuits. Pulse Width Modulated amplifiers in comparison with linear servo amplifiers offer considerable advantages in the Control of DC motors. The major disadvantage of linear servo amplifiers is the excessive power dissipation, due to which the efficiency of the overall system gets reduced, size & weight of the system increases to accommodate necessary cooling apparatus, junction temp. of power semiconductor increase thereby reducing life time of the device and the overall reliability is reduced. Pulse width modulated amplifiers are those which utilise transistors operating in the switching

mode. By switching the transistors on and off into saturation, power losses in the transistor junctions are minimised. If the switching frequency is well beyond the driven system bandwidth, the motor will filter the high frequency components of the modulated signal and respond to the low frequency components or dc level of the signal. There are basically two methods of obtaining a PWM. One is dither method and the other is Limit Cycle method. In dither method, an externally obtained periodic signal of sawtooth, triangular or sinusoidal wave form is added to low freq. input signal and the resulting sum is fed to a switching element. This converts the voltage into a two level signal whose DC level is proportional to the input voltage. In limit cycle method, high frequency limit cycle behaviour of the system when the feed back is closed around the amplifier is utilised. In PSLV, Dither method is used to generate the pulse width modulation.

Two types of amplifier configurations are generally used in PWM generation. They are T configuration and the H bridge. In PSLV the H bridge configuration is used. This has the following advantages. H bridge needs only one supply and transistor's required breakdown voltage settings are reduced by one half of that of T configuration. When switching frequency and power dissipation are considered, the H bridge due to its lower voltage requirements is preferred over the T configuration. But it has inherent disadvantages in that - it requires twice as many as semiconductor switches as does the T configuration and T configuration offers better return isolation that H bridge.

B. <u>SOURCES OF INTERFERENCES IN PWM INDUCTIVE SWITCHING AMPLIFIERS</u>

<u>Inteference Generation:</u>

Pulse width modulated power amps. switching inductive loads generate generally the following types of interferences:

1) Transient noise resulting from inductive switching.

2) HF noise generation in radiation & conduction mode by PWM switching frequency.

3) Heavy switching currents and generation of large magnetic fields.

<u>Inteference Transmission:</u>

The energy contained in an inteference signal can be transmitted from a source to a susceptable unit by means of conductive coupling, a common inductive or capacitive impedence, free space radiation or by any combination of these means. In a launch vehicle, the EMI generated can be transmitted by:

1) Ground loop formation between power & signal grounds and subsequent curruption of signals.

2) Propagation of the Interference to other senstive systems due to improper harnessing, physical location etc.

B1 INTERFERENCE GENERATION

a) Transients:

Inductive kicks and general effects of suddenly collapsed magnetic fields produce transients ranging from sub audio to megahertz region depending on the effective inductance and capacitance in the path of the current produced by the collapsing field. The switching transients in PWM operated inductive loads may get coupled to semiconductor logic devices and falsely trigger them.

- Pulse energy resulting from transients generates broad band EMI and can be transmitted by radiation or conduction. The spectral amplitude depends on transition time & duration of transients. The noise can cause inteference problems to communication and analog circuits. When the inductor load is controlled by a semiconductor switch, the transient may exceed the breakdown voltage of the device and can destroy it.

b) HF Noise Generation:

The pulse width modulated power amplifiers generate a long series of harmonic components of the square wave that typically extend well into low-megahertz region. The energy content of these various harmonics decreases with frequency at a rate that is inversely proportional to some integral order of frequency.

c) Generation of Magnetic Fields

A third manifestation of interference associated with PWM is in the form of magnetic coupling resulting from the switching of relatively large currents.

Each of the three sources is capable of generating objectional interference that can appear on external leads as conducted interference or that couple into the RF sections nearby and create unwanted modulations of carrier.

B2. Ground loop formation:

In the PWM system, common impedence coupling occurs through the PA return and the servo loop signal return, and low level input signal can get corrupted. Further, since instrumentation return may be common for all monitoring systems, if proper isolation is not provided, the PWM amp. return can get coupled to different systems through Telemetry return. This can affect the performance of the other systems. Telemetry outputs also will get corrupted. Added to this, since the error signal generation is from the onboard processor, the coupling will affect the processor return also, which may lead to performance anomaly in the OBC side. Hence it is all the more essential to isolate the onboard computer return and the signal return.

Again improper bunching and routing of the cables in integration phase will lead to cross talk.

C. NOISE REDUCTION TECHNIQUES EMPLOYED IN PWM OPERATED PA DRIVEN CONTROL SYSTEMS - PSLV EXPERIENCE

In PSLV, the sources of EMI due to PWM inductive switching are tackled in two different phases.

In the design phase of the equipment

Attempt is made in the design of the Control Electronics to minimise both the generation and transmission of the EMI.

If max. efficiency is the sole controlling design parameter for PWM PA, very little can be done to prevent the generation of harmonics inherently present in the squarewave. If a sacrifice in efficiency is accepted, pulse shaping techniques can be used to confine and absorb the unwanted harmonics. In PSLV, pulse shaping techniques are not employed.

The interface requirements with other subsystems and EMI levels are well defined and the inputs are communicated to the designer in the design stage of the package itself. This is made possible by a comprehensive design of the powering and return scheme for the overall vehicle. This will enable the designer to make proper interfaces in the control electronics to prevent the transmission of EMI to other systems.

In the Integration Phase:

Noise transmission is minimised by a comprehensive design of the interfaces for the control system with other systems and by suitable grounding and shielding methods in the electrical integration of the subassembly. This also calls for an optimum design of the component layout. It is always better to cluster control system packages together and away from the other subsystems.

The noise reduction techniques employed in these two phases are illustrated in the case study of third stage control system of PSLV.

D. THIRD STAGE CONTROL SYSTEM OF PSLV - A CASE STUDY

The Third Stage of PSLV is a solid motor stage, using flex-seal nozzle control system for pitch & Yaw control. The Flex Seal nozzle control system consists of two independent closed loop servos which position the engine as per the command generated by the vehicle auto pilot system. The basic subsystems of the FNC are electromechanical servo actuators and servo control electronics. The configuration of control electronics contains the following functional blocks.

- Command processing unit
- Error amplifier & Servo compensator.
- Triangular wave form generator.
- Commutation logic circuit
- Drive circuit
- Current sensor
- DC/DC convertors
- T/M interfaces.

The actuators are operated by two brushless motors in order to meet the required torque level and through electronic

commutation. The power amplifier configuration is H bridge. The torque motor is rated for a max. of 50V and 37A.

NOISE REDUCTION TECHNIQUES EMPLOYED

Design Phase

The H configuration used for PWM PA Circuit in 3rd stage of PSLV is given in fig. 1. Diodes D4-D8 act as freewheeling diodes. The transistor selected has a PIV of 400V for a max. current of 60A which will take care of any reverse voltage generation.

The current ripple for the PWM amplifier is directly proportional to both supply voltage and switching period and inversely proportional to motor inductance. Generally in any given application, the supply voltage and motor inductance will be fixed so that, switching frequency will decide the current ripple. Hence in order to minimise the current ripple, it is desirable to have a higher PWM frequency. Again, the selection of PWM frequency should be in relation to motor time constant also.

The PWM frequency chosen is 10KHz since motor time constant is 1 msec. Hence an empirical value 10 times greater than 1 KHz is chosen. This will help in reducing the ripple current & the ripple-torque. Since for most of the time during flight the PA will be operating with 50% duty cycle, high PWM frequency will minimise the ON/OFF time of the transistor and thus transistors will be exposed to transients for smaller durations only.

As seen in the circuit, two large capacitors, C1 and C2 are placed across the 50V supply. This has 2 purposes.

1. Because of diode free wheeling action, especially during periods of rapid deceleration from near maximum motor speeds, substantial energy can be transferred from the motor back into the amplifier dc supply. Owing to the high efficiency of the PWM servo amplifiers, min. dissipation of this returned energy is allowed. Consequently, the returned energy is stored in the power supply. The result of this energy storage is the temporary increase of DC bus voltage. Moreover in 3rd stage case, since supply source is a battery, this phenomenon will charge the battery in PWM frequency which will reduce the battery life. In order to prevent this and to ensure that voltage rise does not result in catastrophic failure of the amplifier, sufficient capacitance has to be provided.

2. The capacitor will act as a snubber across the inductor and will reduce the hf emission content due to PWM switching.

The snubber circuits are generally used to minimise the dv/dt rate in order to protect the switching devices. However in practical applications, snubber circuit design is critical in view of average ripple current and bidirectional flow of current.

a) Transients:

In Third stage control system, the transients are suppressed by (1) Free wheeling diodes across the transistors.

(2) A large value capacitor across the power supply located inside the package.

The 10KHz switching frequency, and the 10KHz triangular dither wave will produce harmonics in the higher freq. ranges. No attempt is made to reshape the pulse train to bring down the harmonic contents. The switching transistors are housed separately in a compartment independent of the servo electronics so as to minimise the effect of conducted and radiated coupling of the harmonics. Moreover the capacitors are mounted very close to the switching transistors to enable partial snubbing.

The servo electronics and driver amplifier circuits are totally isolated using opto coupler circuits. Hence power and signal grounds are isolated preventing common impedence ground & return loops. This also prevents the PWM switching frequency from getting coupled to the signal lines (Fig. 2). The separate grounds used for power and servo controller signals are shown in the fig2. Similarly separate supplies are used for PA and servo controller (50V for PA and 28V for controller).

Separate DC/DC Convertor windings are selected for Telemetry monitoring of the Control Electronics parameters. Thus instrumentation returns are isolated from signal grounds by a definite impedence (gen. of the order of 200K). This reduces the coupling of PWM signal freq. to the other systems in the stage.

The usage of brushless dc motors & electronic commutation have the added advantage of elimination of commutation noise.

(b) <u>In the Integration Phase</u>:

The magnetic field generated by 37A inductive switching currents can get coupled to other sub systems through conduction and radiation. Improper interfaces and return couplings can further worsen the situation by permitting transmission of the generated noise. These problems are tackled in the subassembly electrical integration phase. This involves:

1) a comprehensive interfacing, grounding & shielding scheme

2) component layout.

In third stage of PSLV, Control System components are grouped together and are located away from susceptible components. This enables to minimise the harness length of cables carrying PWM signals.

(i) <u>Harnessing Scheme:</u>

Since related systems of the CE are all located in a single deck plate, electrical cabling is minimised & totally isolated from the other sensitive cables of the stage. In the deckplate itself, power & signal lines are routed separately to the extent possible. For signal & power lines, twisted shielded wires are used. For PA O/P and actuator lines, magnetic shielding is provided

using Tecknit shield material. For feq. >10KHz, it offers >60dB EMI attenuation for H fields and >110dB attenuation for E fields Telemetry signals of CE are separately bunched together and routed. They are also provided with shielding.

ii) <u>Return line configuration</u>

The Return circuit configuration for 3rd stage control electronics is shown in fig. 3.

It is ideal to have separate grounds for signal and power for the system operating at low frequencies, and high currents. Thus as mentioned earlier, separate convertor windings are used to power the servo amplifier circuits and Telemetry circuits. Again, separate batteries are used for servo amp. supply & power amplifier supply. Opto isolators separate the return of servo side and PA side. The CE error signal I/P lines are buffered from NGC return with an impedence of atleast 100K as shown. This will help to minimise the conducted interference .

In view of electrostatic discharge, in launch vehicles it is mandatory to provide bleeder resistance from bat. returns to chassis. Because of this there will be a 20K path between 28V primary return and 50V PA return. However this coupling is made at the nearest point and loop current through the path is minimised.

iii) <u>Shielding & Grounding:</u>

Use of twisted shielded cables with 90% shield effectiveness of braid helps in reducing magnetic couplings.

Equipment chassis & shield are not used for signal return paths.

- Each signal line is given independent return line running as close as possible (using twisted pair). Thus the loop area is reduced and common impedences with other signals avoided.

Though shielding effectiveness reduces with increasing frequency for braided shields, PWM operating frequencies are of the range of 20 to 30 KHz max. where, using single copper braid, approx. 60dB shielding effectiveness is obtained.

To be effective, shields also must confirm to proper grounding methods. In Launch vehicle scenario it is not possible to have a uniform policy of grounding methods. The minimum voltage point in the loops has to be found out and the shield has to be connected there.

In third stage control electonics, the shield is connected to the chassis at the O/P of PA (at the driver point) for the PA shielded lines. For error signals the shield is connected at the package input. Thus single point gounding system in parallel connection mode is used for power and signal grounds. The configuration is given in fig. 4.

<u>CONCLUSION:</u>

Pulse width modulated power amplifier switching inductive loads generate transient noises, HF noise, mag. fields due to heavy switching currents and transmission of these noises due to ground loop formation and improper harness

ing. In PSLV design, these problems are tackled in two phases viz., design phase & integration phase. Attempt is made in the design phase of the Control Electronics to minimise the generation of EMI, taking into consideration basic functional requirements. By comprehensive design of the powering and grounding scheme for the overall vehicle, and making use of these inputs in the design as well as integration phase of the system, generation & transmission of noise is minimised.

The Third stage control system with actuators was tested in controlled environment of the EMI lab for conducted and radiated emission. The emission levels were found to be within accepted limits as per MIL-461. In the integrated configuration of the subassembly, with the adoption of specific grounding scheme (Ref. fig. 4), no serious noise problems were encountered. (Initial scheme envisaged shielding of both ends of the signal lines from on board processor to 3rd stage control electronics input in view of RF field generation due to the proximity of transponders and transmitters). Plots (1), (2) and (3) give the feed back signal O/P before the adoption of the particular shielding configuration while plots (4) and (5) give the feed back O/Ps after the adoption of the shielding configuration. Plot (6) gives the convertor O/Ps and Temp. mon. near control system. It can be seen that the max. level of noise is only 30mV.

Thus it can be seen that by proper design of circuits, layout design, harnessing shielding & grounding methods the noise coupling can be minimised.

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REFERENCES

1. Basic PWM Servo Amplifier Theory - Inland Motors

2. Pulse width modulated DC Control A Parameter Variation study with current loop Analysis.

   - Charles K. Taft, Member IEEE & EDW V. State

   No.4 Vol. IECI-26 - 1979

3. Principal EMI Coupling Paths. - EMC series - Instructor Dr. J. White

4. Design guidelines for Electromagnetic compatability - HP

5. Protection & Switching Aid Networks for Transistor bridge invertors .
   - KS Rajasekhara, Joseph Vithayathil, V. Rajagopalan
   - Vo. 1 IE33, No. 2 May 1986.

6. Design & Analysis of Pulse width modulated Amplifiers for DC servo systems.
   - Jacob Tal Vol. IECT-23, No. 1 Feb. 1976.

7. On Switching inductive loads with Power transistors - Ralph E. Locher

8. EMC Constraints for harness design
   - E. Schachwitz

9. EMI Control consideration for PSLV.

10. Configuration Control Document for PS3 FNC CE.

11. Tecknit - Production Catalogue & Application Notes.

12. Design of Solid State Power Supplies
   - Eugene R. Hnatek

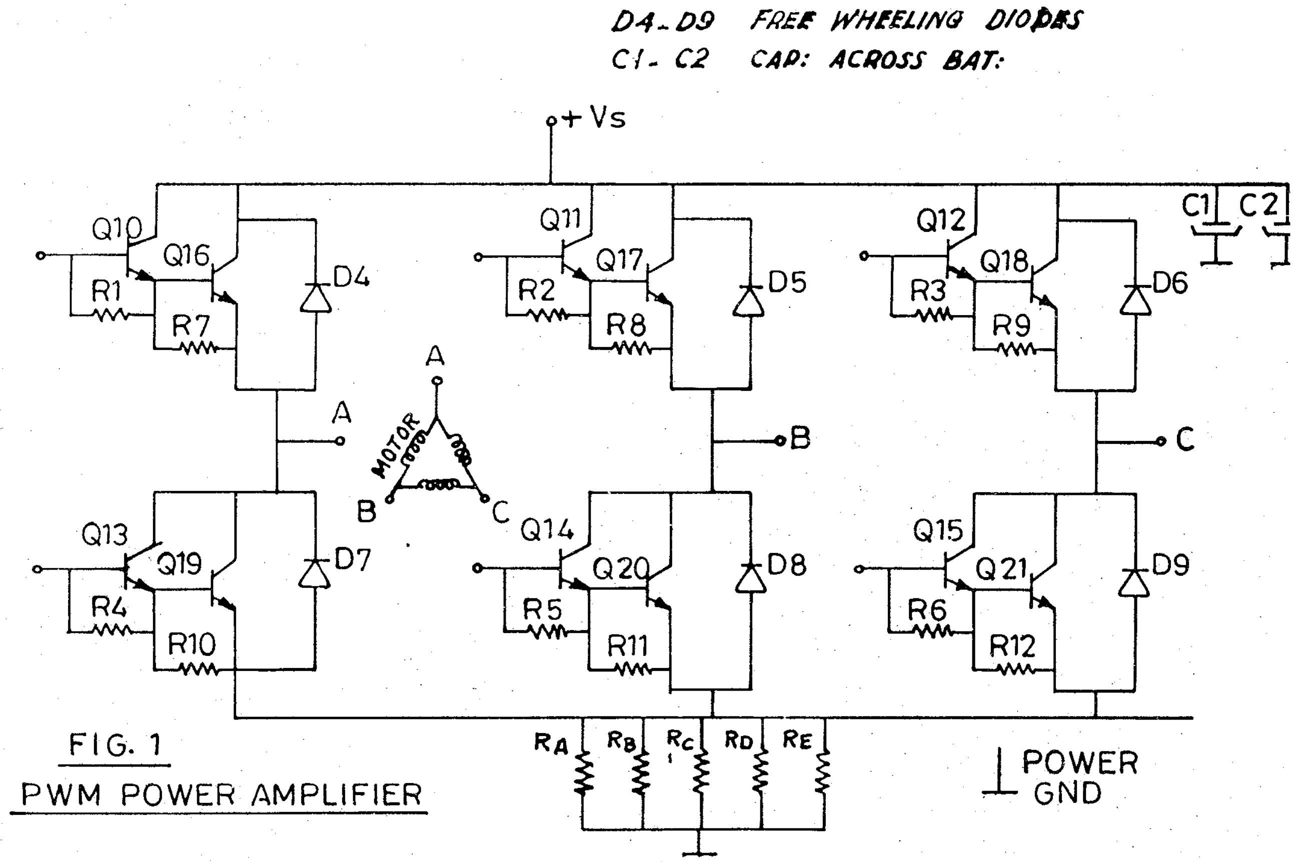


FIG. 1
PWM POWER AMPLIFIER

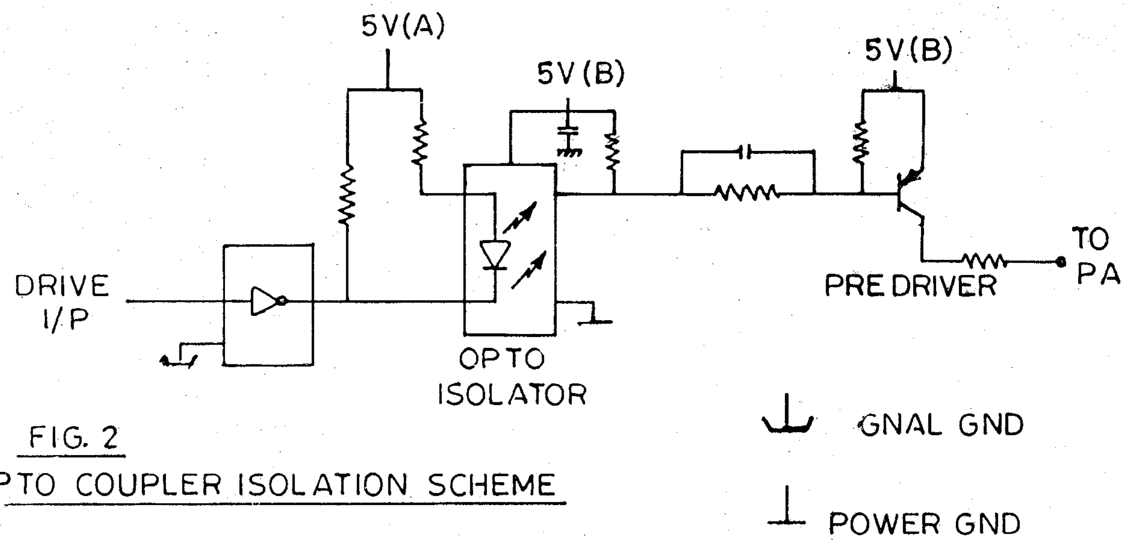


FIG. 2
OPTO COUPLER ISOLATION SCHEME

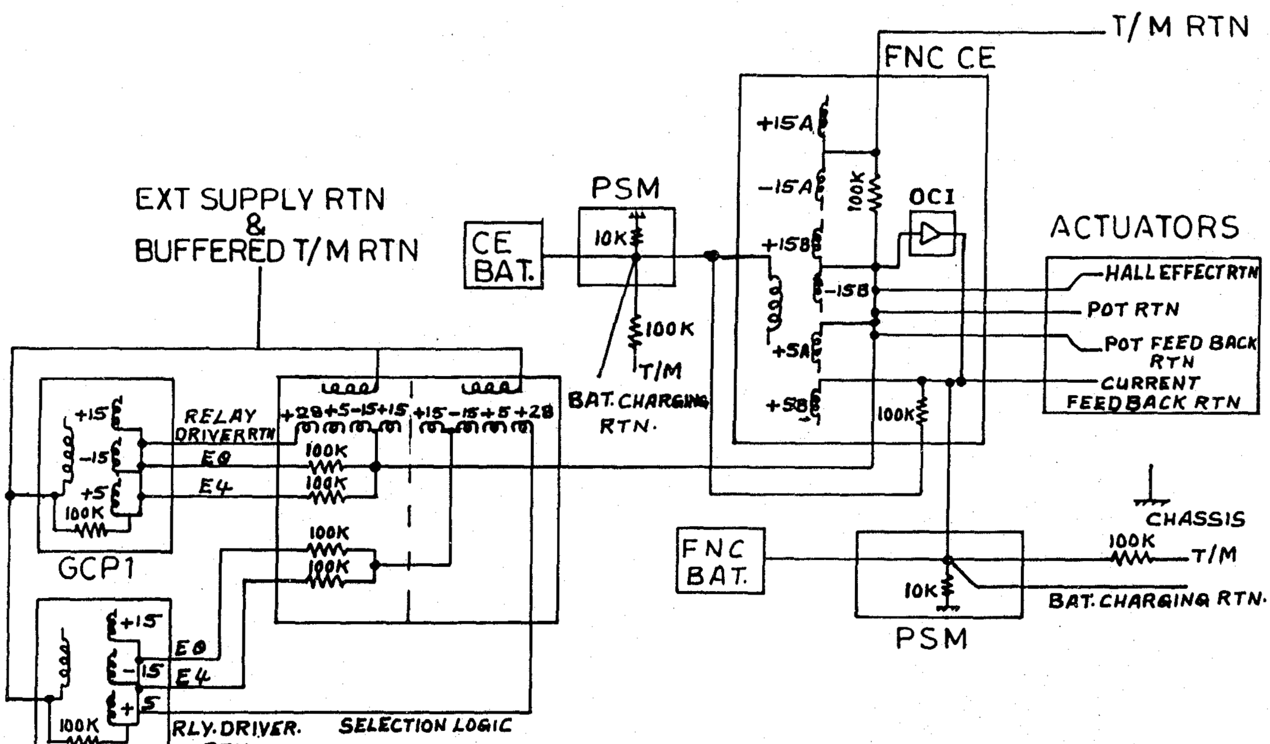


FIG. 3. RTN LINE CONFIGURATION

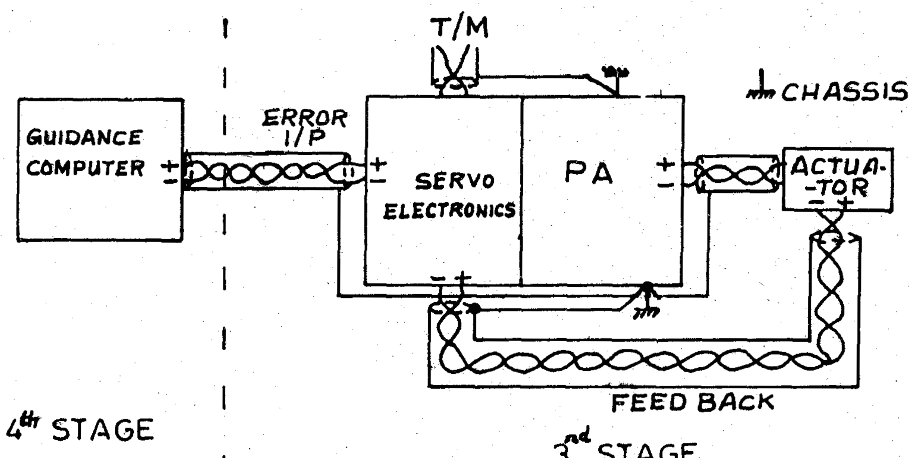
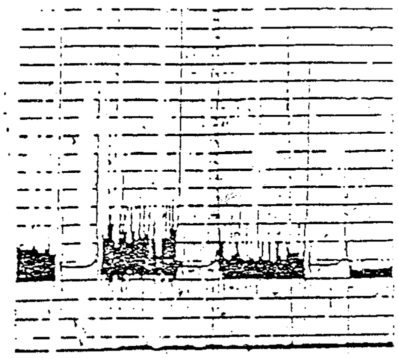
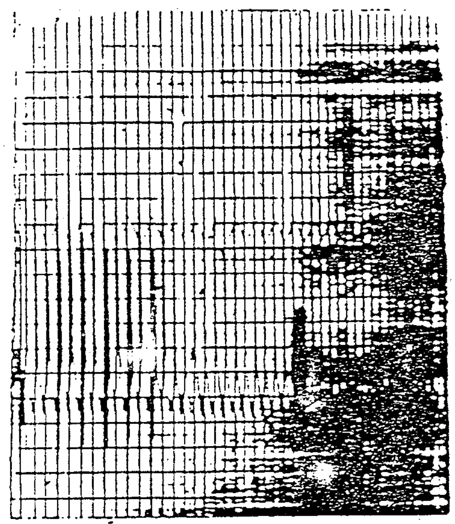


FIG. 4

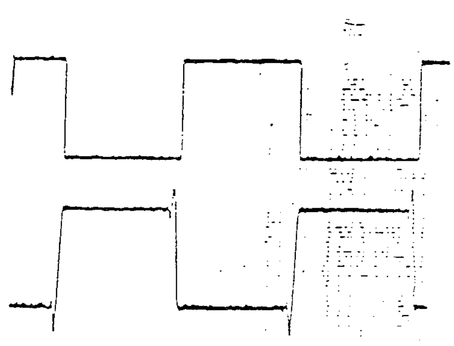
GROUNDING & SHIELDING SCHEME



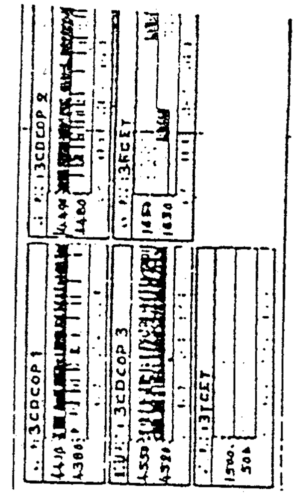
PLOT-1



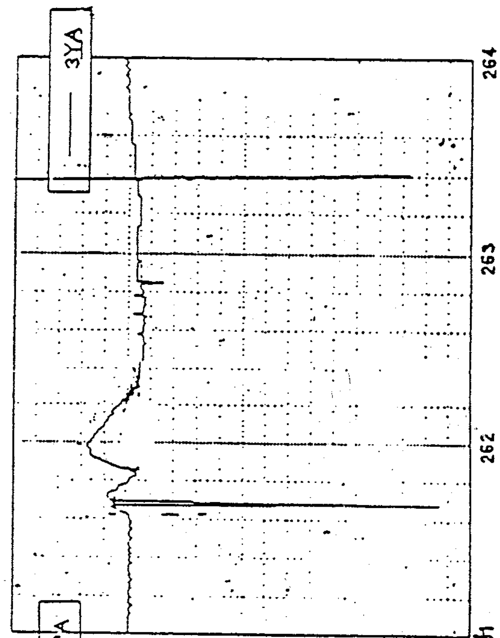
PLOT-2



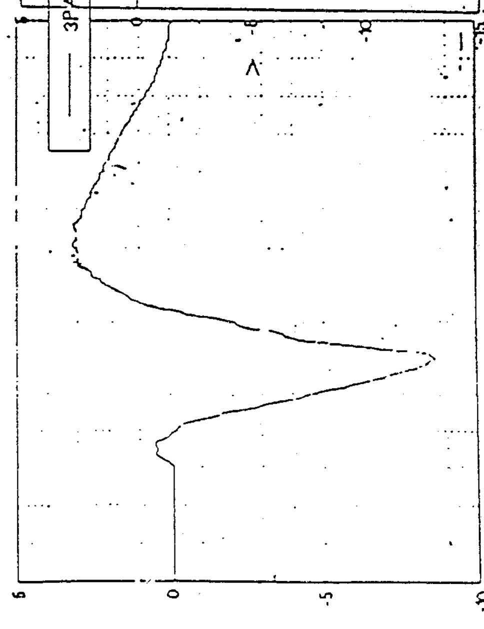
PLOT-3



PLOT-6



PLOT-5



PLOT-4